

## Chemical Engineering in Space

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### Abstract

The state of the art in launch systems uses chemical propulsion systems, primarily liquid hydrogen and liquid oxygen, to provide the energy necessary to achieve orbit and escape the bonds of Earth's gravity. In the future there may be other means available; however, currently few of these alternatives can compare to the speed or the ease of use provided by cryogenic chemical propulsion agents.

Cryogenics, the science and art of producing cold operating conditions, has become increasingly important to our ability to travel within our solar system. The production and transport of cryogenic fuels as well as the long-term storage of these fluids are necessary for mankind to travel within our solar system. It is with great care and at a significant cost that gaseous compounds such as hydrogen and oxygen are liquified and become dense enough to use for rocket fuel.

As our explorations move farther away from Earth, we need to address how to produce the necessary fuels to make a complete round-trip. The cost and the size of any expedition to another celestial body are extreme. If we are constrained by the need to take everything necessary (fuel, life support, etc.) for our survival and return, we greatly increase the risk of being able to go. As with the early explorers on Earth, we will need to harvest much of our energy and our life support from the celestial bodies. The in situ production of these energy sources

is paramount to success. Due to the current propulsion system designs, the in-situ processes will require liquefaction and the application of cryogenics.

The challenge we face for the near future is to increase our understanding of cryogenic long-term storage and off-world production of cryogenic fluids. We must do this all within the boundaries of very restricted size, weight, and robustness parameters so that we may launch these apparatus from Earth and utilize them elsewhere. Miniaturization, efficiency, and physically robust systems will all play a part in making space exploration possible; however, it is cryogenics that will enable all of this to occur.

## **Keywords**

Cryogenics, hydrogen, insulation, oxygen, space, storage

## **Introduction**

Space exploration is currently dependent upon cryogenics for many different reasons. The most efficient propulsion systems utilize cryogenic fuel and oxidizers, while satellites take advantage of superconducting properties using cryogenics cooling. As man extends the limits of exploration farther into our solar system, cryogenics will enable our survival and allow us to return to Earth. The challenge for us is to develop the technologies that will permit production and long-term storage of the cryogens while minimizing the size and weight of these systems.

## **Both Science and Art**

Cryogenics is both the science and art of producing cold. In scientific terms, cryogenics is the low-temperature physics and chemistry associated with materials, especially liquids at or below 123 kelvin. Cryogenics is an industry and area of technology that provides the neces-

sary commodities to allow reasonable access to space and space technologies. "Cryogenics is a very diverse supporting technology, a means to an end and not an end in itself." [1]

### **Principal Cryogenics for Aerospace**

One area of cryogenics that has extensive aerospace applications is liquid cryogenics. There are four principal cryogenics utilized in, on, and around space vehicles – hydrogen, oxygen, nitrogen, and helium. Hydrogen and oxygen are primarily used for propulsion. The liquid hydrogen and liquid oxygen provide the highest impulse power of any liquid fuel available at this time. Hydrogen and oxygen are also clean burning and environmentally friendly. Current work in the propulsion community is focused on the densification of these two liquids to enable increased quantities of propellants to be loaded onto a spacecraft.

Nitrogen is primarily used as an inert fluid. The liquid nitrogen can be used as a test fluid for safely simulating liquid oxygen within systems and support operations. Gaseous nitrogen is used in large quantities for purging, inerting, and pressurizing innumerable systems, including the liquid oxygen tanks. NASA uses gaseous nitrogen for many things, from drying to fire fighting. Liquid nitrogen is also used for many things, from supplying clean gas to freezing hydraulic fluids.

Helium is used as a purge and pressurant gas for liquid hydrogen storage tanks as well as a leak detection fluid. The use of the helium in leak detection can be found in nearly every aspect of the space program. Helium fluid cryocoolers are used extensively in spacecraft to provide the cooling necessary for superconducting sensors and electronics.

### **Production and Storage on Earth**

The production of cryogenic fluids is primarily accomplished through refrigeration either by the Carnot or the Joule-Thomson processes. These processes are energy intensive and are

therefore extremely focused on energy recovery systems. The low-temperature compressor-expanders (combanders) utilized in standard air separation facilities are extremely efficient, with thermal efficiencies on the order of 90 percent. The primary means of storing liquids is by the time-honored vacuum-insulated vessel or dewar. The choice of insulation materials used within the vacuum annulus is highly dependent upon the cost and critical storage times required. In larger vessels the use of low-cost materials (such as perlite or other calcined materials) is quite common. In smaller or more critical applications, the insulation of choice is a multilayer composite system (MLI) using alternating layers of a paper or fiber material with a reflective foil or metallized Mylar. The choice of insulating materials is primarily driven by economics. Some newer materials being developed are starting to minimize the difference between the highly efficient (i.e., expensive) MLI and the less efficient (i.e., inexpensive) perlite. Some of the newer materials are the aerogels or similar silica-based products. These products show promise especially in the area of moderate vacuum levels. [2] A large part of the cost of storing cryogenics is the maintenance of the vacuum space between the inner and outer tank. Small reductions in the required vacuum levels can translate into very large labor savings. [3]

### **Cryogenics in Orbit**

Satellite systems quite often require very low temperatures to support the instrumentation platforms. These orbiting instrumentation platforms are becoming more and more complex and high tech. Large numbers of sensors, instruments, signal processing equipment, communications amplifiers, etc., require part, if not all, of the system to operate in a superconducting manner. Many of the current systems qualified for flight utilize low-temperature superconducting materials and require temperatures below 15 kelvin. [4]

The cost and the weight penalty associated with providing liquid helium to cool these devices have spawned an entire industry designing and building cryocoolers. Cryocoolers pro-

vide a mechanical means of delivering low-temperature refrigeration for long durations without any external intervention. Cryocoolers transitioned from the laboratory to the space industry very easily. Only the space industry was able to afford the relatively high cost of cryocooler construction initially. The reliability of the devices versus a liquid storage (one-time use) system is obvious.

### **Nonterrestrial Cryogens**

Efficient storage of cryogenic liquids on other planets or celestial bodies such as the Moon and Mars is paramount for the successful exploration of our solar system. Initially we will have to transport at least part, if not all, of our fuel for survival on and return from these off-world locations. The cryogenic losses that occur during the transportation to or while on the surface of another planet simply increase the quantities that must be boosted into orbit and then transported with the mission.

In addition, the equipment that stores the cryogens carries a significant penalty with regard to the overall cost of the mission and ability to get the equipment into space. The current launch system economics dictate that each kilogram of material put into orbit costs \$22,000. Once in orbit it must reach its destination and land safely. [5] In order for a mission profile to be within the cost constraints of expected funding availability, the costs need to be less than \$4,800 per kilogram. [6] The need to reduce this cost as well as the weight of the equipment becomes paramount.

### **In Situ Resource Utilization (ISRU)**

The effective exploration of Mars depends on being able to utilize the available resources to produce propellants from the Martian atmosphere. The propellants could be utilized in two areas: (1) as fuel and oxidizer for the return trip to Earth and (2) as a backup component for

life-support systems. The In Situ Propellant Production (ISPP) component of ISRU is the enabling technology to allow humans to realize the goal of performing meaningful work while on the surface of Mars. [7]

The commodities required to make the ISPP a reality are carbon, oxygen, and hydrogen. Since the hydrogen component of the propellant mix is very light, a spacecraft can bring it directly from Earth. The remaining required raw materials, carbon and oxygen, can be found in abundance in the Martian atmosphere in the form of carbon dioxide. The Martian atmosphere is composed of approximately 95-percent carbon dioxide, with small amounts of other components such as nitrogen and argon.

By using a combination of low power and cyclic processes, it is envisioned that a small plant will be capable of steadily producing the necessary oxygen and then liquefying it. This small facility will be able to provide oxygen to combust the fuel and for breathing air as well as excess water for consumption or further production of fuel and oxidizer. Processes need to be efficient and effective. While individual processes will not carry severe penalties, the overall efficiencies of the entire complex need to be in excess of 90 percent. The products/byproducts of the various systems and processes must be recycled and reused whenever possible.

### **Minimization**

In the scope of space travel, the concept of small is a necessity. The entire payload size for one of the proposed Mars demonstration missions was set at a total of 48 kilograms. This included all pumps, fans, compressors, reactors, and any associated piping and controls. This puts the actual "plant" size on the scale of a small laboratory apparatus setup. This small-scale requirement drives many of the manufacturing and maintenance requirements. The machinery included in the equipment must be lightweight and small enough to fit into the overall scheme, yet it must also be robust enough to operate unattended.

## Long-Term Storage

One of the most critical requirements at this time for a return mission from another celestial body is the long-term storage of liquid hydrogen and other cryogenic fluids. The duration of the storage required for an extraterrestrial mission is on the order of years. During a Mars mission, for example, the duration of storage requirements are from three to four years. Significant losses of the cryogenics while in storage are unacceptable. The Mars Reference Mission describes a duration of 888 to 924 days. [6] The temperatures necessary to maintain the liquid cryogenics are relatively straightforward. The spacecraft and the liquid dewars must maintain the fluids at or below the boiling points of the contained liquids; for liquid hydrogen that is 20 kelvin. During the flight from Earth to Mars or the Moon there is very little heat input due to convection or conduction to the surrounding space. The heat gains and losses are primarily due to radiation effects. The sun and the planets radiate energy out into space where the spacecraft must then either absorb and reradiate or reflect much of the energy. The sun acts like a black body radiating at a temperature of 5760 kelvin, while the Earth can be approximated by a black body at 254 kelvin, which effectively adds heat to the spacecraft. [8] In addition, the majority of space is absorbing heat from the spacecraft at an effective temperature of 3 kelvin. Therefore, the insulation systems utilized will need to protect against these heat inputs. Thermal stability for the spacecraft itself is usually a controlling factor, and the cryogenic storage system can utilize the cold of space to enhance the long-term storage ability. Once on a planet surface, the heat transfer equations are more involved as the convective and conductive terms become significant and must be considered. For our purposes, the average temperature of Mars is estimated to be 210 K. [9]

## Summary

Cryogenics is significantly involved in the process of achieving space exploration. It is an enabling technology that will provide the necessary support and capability so that Man can reach out farther into our solar system and beyond.

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